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Design and simulation of SMES system using YBCO tapes for direct drive wave energy converters

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Abstract—The ocean represents a huge energy reservoir since wave can be exploited to generate clean and renewable electricity; however, hybrid energy storage system is needed to smooth the fluctuation. In this paper a hybrid energy storage system using Superconducting Magnetic Energy System (SMES) and Li-ion battery is proposed. The SMES is designed using Yttrium Barium Copper Oxide(YBCO)tapes which stores 60kJ electrical energy. The magnet component of the SMES is designed using global optimization algorithm.Mechanical stress, coupled with electromagnetic field,is calculated using COMSOL and Matlab. A cooling system is presented and a suitable refrigerator is chosen to maintain a cold working temperature taking into account four heat sources. Then a micro-grid system of Direct Drive Linear Wave Energy Converters(DDLWECs)is designed. The interface circuit connecting the generator and storage system is given. The result reveals that the fluctuated power from DDLWECs is smoothed by the hybrid energy storage system.The maximum power of wave energy converter is 10 kW.

Index Terms—Hybrid energy storage system, SMES magnet design,Cryocooler power, Control circuits.

I. INTRODUCTION

A LARGE portion of renewable sources have been connected to power grids in the past decade. Power available for extraction from renewable energy sources fluctuates dramatically depending upon the environmental conditions e.g. wave strength and sun light, which can vary on the time scales from seconds to days. Because of their intermittent nature, renewable energy sources present significant challenges to power grids in managing their stability, security and reliability. As renewable penetration increases in these systems, it will be economically and environmentally beneficial to smooth the generated power and hence make the best use of local renewable energy sources. Due to the large variation in load/generation balance of renewable energy sources, an energy storage system with the capability of fast response to power fluctuations on a short time scale of seconds to minutes will have the greatest value[1,2]. Additionally, it

needs to have a large energy density in order to deal with power imbalances on a longer term basis. For microgrids, where power levels are in the range of a few megawatts, there is one technology for the required energy density: electrochemical batteries, and three prime candidate technologies for the required power density: SMES, supercapacitors and flywheels.

Although they have large energy densities, the power density, life cycle and response speed of electrochemical batteries usually are very limited. Therefore they are not able to address the challenges of balancing frequent power fluctuations on a short time scale of seconds. Even if used, their life will be significantly reduced and hence result in substantial increase of operation costs. On the other hand, SMES, supercapacitors and flywheels, have large power densities, large duty cycles and fast response speeds. Compared with flywheels and supercapacitors, SMES systems have significantly larger power densities and module power ratings as shown in Figure 1 [3]. In addition, they have advantages such as high round-trip efficiencies and solid-state operation. Therefore they are able to significantly increase the performance of energy storage systems.

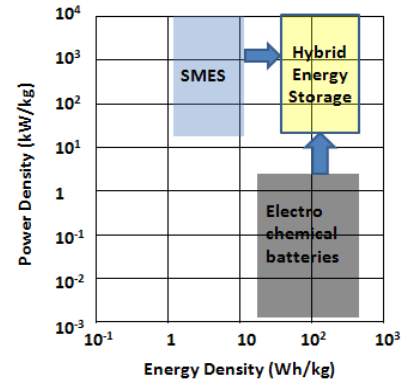


Fig.1 The configuration of Hybrid Energy Storage System

This paper is investigating a hybrid energy storage system using batteries and SMES systems for integrating wave energy generators to power system. The SMES magnet design will be presented in Section II, followed by a system simulation in SECTION III. The conclusion is presented in SECTION IV.

II. SMES MAGNET DESIGN

A. Requirement of the SMES system for a wave generator

Marine wave power is a vast and largely untapped source of energy. DDLWEC is one of the most promising technologies of harnessing waves for electricity generation. The electrical

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output profile of DDLWECs represents an unusual waveform for electrical power conversion systems to handle. There is large fluctuation of output power from DDLWECs in each wave, which results in a high ratio of peak power to the long term average value. The problem of power fluctuations can be addressed by fast responding energy storage devices.

The ocean waves, having periods from 5 to 15 seconds, normally have the feasibility and the potential for driving DDLWECs to generate electricity. SMES have large power density and fast responding time, which could easily meet the system's requirement related to power and speed. The available wave power, that is ready for extraction from the ocean, can be predicted from the weathercast over a certain time. Hence, the output power generated from a particular DDLWEC can be evaluated. The energy capacity of SMES is calculated to handle the difference between the maximum and average power from a DDLWEC at a specific location over a certain time. Taking the integration of the power difference over time gives the maximum energy that needs to be stored by the SMES. A 60 kJ SMES is designed to handle the frequent power fluctuation caused by a particular DDLWEC in each wave period.

B. Material properties

The second generation (2G) High Temperature Superconductor (HTS) is a state-of-the-art conductor with a high irreversibility field and critical current density in an external magnetic field. They can operate either with liquid nitrogen, gas helium, or commercial cryocoolers, thereby eliminating the requirement of expensive liquid helium. To design the magnet component of the SMES, the 2G HTS YBCO tape SC4050, produced by SuperPower, is adopted.

The main properties of the tapes are listed in Table 1. The tapes have a width of 4mm and a thickness of 0.1mm. Figure 2 presents the critical current, I_c , in different external magnetic flux density at 65K, which was provided by Superpower. The critical current of the tape is 400A without external magnetic field. Apparently, its critical current varies widely in the range and this feature should be considered in the magnet model.

C. Magnet design

The target of magnet design is to achieve the maximum energy with the least length of tape. Normally, solenoid and toroid are two types of SMES. Solenoid coils are easy to build and have higher energy densities. In our design, stacked double pancake structure, which is basically a solenoid, is selected. According to

$$E = \frac{1}{2} LI^2 \quad (1)$$

Where E is the energy stored in the coil, L is the inductance of the coil and I stands for the current. It is clear that the inductance and current in the coils determine the stored energy. The inductance of coils depends on the configuration [4]. At the same time, the critical current is mainly constrained by the maximum field to the tapes according to Figure 2.

Global optimization algorithm is incorporated into finite element method (FEM) model with COMSOL Multiphysics package and Matlab. The flow chart of the algorithm is shown in Figure 3 [5].

TABLE 1 CHARACTERISTICS OF YBCO TAPE

Specification	Value
Critical current (77K, self field)	400A
Average thickness	0.1mm
Width	4mm
Maximum tensile stress	>550MPa

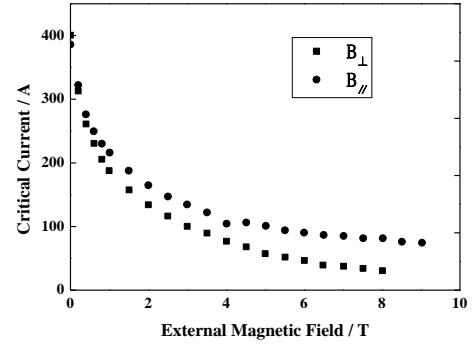


Fig. 2 The $I_c(B)$ dependence of magnetic density flux in parallel and perpendicular direction

First, one configuration for the magnet is chosen, which includes tape length, inner radius and the number of pancakes. Due to Maxwell theory,

$$\nabla \times B = J \quad (2)$$

if a certain current density J is applied to the section area, the magnetic flux B and magnetic magnitude H can be calculated in COMSOL. Then the energy stored can be integrated over the section area since

$$E = \int B dH \quad (3)$$

Also, the critical current of this configuration can be determined by the magnetic flux density combined with the data in Fig. 2. The final optimized configuration of the SMES magnet is shown in Table 2.

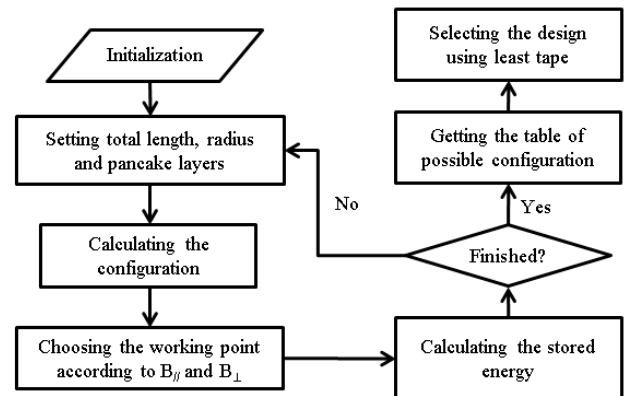


Fig. 3 Flow chart for optimization process

The magnetic field contour reveals that the maximum magnetic field locates in the center of inner edge of the coil, which is about 5T.

TABLE 2 DESIGN SPECIFICATION OF
THE 60kJ HTS MAGNET

Parameter	Quantity
Conductor length	8200m
Inner radius	100 mm
Outer radius	180mm
Number of double pancakes	6
Height	60mm
Turns	7800
Inductance	24.5H
Tape critical current	80A
Operating current	70A

D. Mechanical force

Since the current running through HTS is considerably large, Lorentz force should be analyzed to ensure the mechanical stability of the magnet. The mechanical force field, coupled with electromagnetic field, is calculated using FEM. From mechanics theory, the balance equation is valid in the coil,

$$-\nabla \cdot \sigma = J \times B \quad (4)$$

where σ is stress tensor in the coil, J is current density in the section area, B is local magnetic flux density [6]. Equation (4) means that mechanical stress is triggered by the Lorentz force related to the operating current and magnetic flux density.

Boundary condition is very important in FEM simulation. In our model, it is assumed that

$$u_z = 0, \quad \text{in inner edge of the coil}$$

where u_z means the perpendicular displacement in Figure 4 which shows the stress distribution on the section area. The maximum stress locates on the inner edge of the coil. The maximum von Mises stress is 43MPa, which is within the permitted range of YBCO tape, so the SMES is mechanically stable in operation.

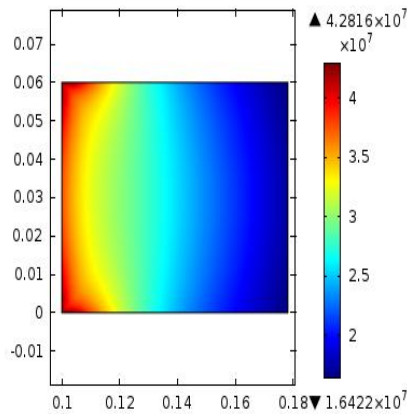


Fig. 4 Stress distribution in half of the right half of the magnet (Pa), the x axis is the magnet radius direction, the z axis is the height direction.

E. Current lead design

Current leads connect the superconducting coil to the room temperature power supply which bring in heat from the ambient

surroundings. Current leads are made from brass for their balanced properties in conductivity for current and thermal flow.

The aim for current lead design is to minimize the heat transferring along the lead. The heat sources are divided into two parts: the heat due to the resistance and the heat flow due to temperature difference between two ends. High temperature end is in 300K, while the low end is 65K. According to [7], the thermal conduction can be minimized when the length/cross-area ratio of conduction cooled current lead has a relation:

$$\frac{l}{S} = \frac{\left(\frac{C\Delta T}{\rho}\right)^{0.5}}{I} \quad (5)$$

Where l is the length of the current lead, S is the cross-sectional area, C is average thermal conductivity of the lead material, ΔT is the temperature difference between warm and cold ends. The minimum thermal flow through the current lead can be calculated as:

$$Q_{lead} = 2 * I \sqrt{\rho C \Delta T} \quad (6)$$

As shown in TABLE 3, the heat conduction through the current lead is 9W.

F. Cooling system design

As it is noted previously, the operating temperature of our design is 65K. Cooling and thermal insulation systems are needed to maintain the cold temperature in the operation of the SMES.

Fig. 5 shows a cryogen free conduction-cooled magnet system.

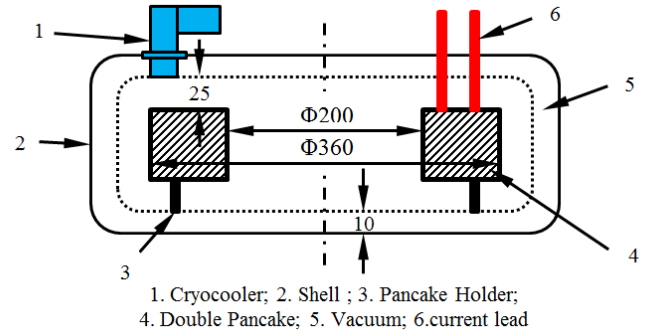


Fig. 5 Schematic of cooling and thermal insulation system

Total thermal load of cryogen magnet includes four components:

1. Conduction loss in the coils.
2. Radiation between the coil and the steel shell, i.e. heat flux through the vacuum.
3. Thermal conduction through the current lead.
4. Other thermal load through the mechanical support components.

All the thermal loads are listed in TABLE 3. The total thermal load in the SMES is 28W. Assuming an efficiency of a cryogenic refrigerator is 30, the power of the refrigerator should be more than

$$P = 30 \times 28W = 840W$$

TABLE 3 THERMAL LOAD IN THE SMES

Thermal load	Value (W)
Conduction loss	8
Radiation flow	3
Current lead flow	9
Holder flow	8
Total	28

III. APPLICATION IN A WAVE GENERATOR

A. Application in a hybrid energy storage for a wave generator

A hybrid energy storage system using 60kJ SMES and 15AH (Amps*Hour) Li-ion battery is designed to balance the output power of a 10kW wave generator.

The DDLWEC generates electricity with varied frequency and amplitude. The generated AC powers from DDLWECs are controlled rectified to DC by an AC/DC converter as shown in Figure 6. The DC link provides a best location for the connection with energy storage systems.

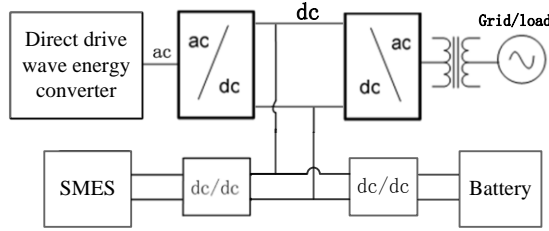


Fig.6 A micro-grid system of DDWECs with a hybrid energy storage system

The characteristic power fluctuation caused by DDLWECs can be addressed by SMES in wave cycles up to ten's seconds since they have fast response speeds and large power densities [8]-[10]. A composite system of SMES and Li-ion battery are chosen to maintain the DC link voltage and output stable power to the grid. The Li-ion battery system is controlled to handle the long term power fluctuation as it has high energy density but relatively slow response speed. The SMES is used to assist battery to smooth the frequent power fluctuation on a short term basis, and hence extend the service life of batteries.

The SMES and battery need to use different DC/DC interface circuits for exchanging energy with the DC link, as shown in Figure 7. When the DDLWEC generates excessive power, the interface circuits control SMES and battery to absorb the redundant power from the DC link and maintain a desired DC link voltage. When the DDLWEC generates powers smaller than the load demand, the interface circuits control SMES and battery to release power for meeting the load demand and maintaining a constant DC link voltage. Due to page limit, the control methods of the interface circuits will be introduced in detail in another paper.

Figure 8 shows the output waveforms of a particular DDLWEC driven by a wave, which has 1.2 meter amplitude from 0-5s, 0.8 meter from 5-15s and 1.2 meter from 15-20s.

The fluctuated power from DDLWEC is smoothed out at the DC link by the hybrid energy storage system, thus a stable output power can be further converted and dispatched to the grid or local load.

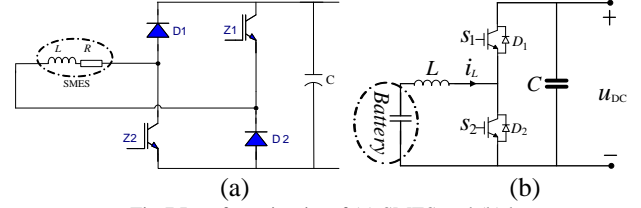


Fig.7 Interface circuits of (a) SMES and (b) battery

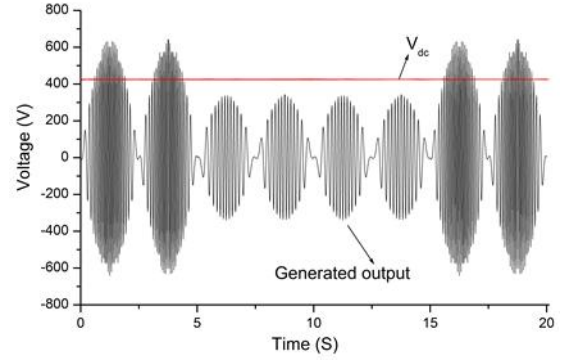


Fig.8 Simulation results of the generator waveforms and maintained DC link voltage

IV. CONCLUSION

The optimal configuration of 60kJ SMES for a wave generator was achieved based on electromagnetic field simulation. The stress due to Lorentz force in the coil was calculated and the maximum stress in the coil was 43MPa which was smaller than the critical tensile stress. Current leads were designed to minimize the thermal flow. The schematic chart of the cooling and insulation system was presented and the required cryocooler power was calculated. The hybrid SMES-battery energy storage system could be used to flat out the power fluctuation of wave energy converters and ensure that stable power output to be dispatched to the grid or local load. The control circuit was presented and the simulation result has shown that the fluctuated power from DDLWEC was smoothed out at the DC link by the hybrid energy storage system.

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